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Why Are Neutrinos Light? – An Alternative

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Abstract

We review the recent proposal that neutrinos are light because their masses are proportional to a low scale, f, of lepton flavor symmetry breaking. This mechanism is testable because the resulting pseudo-Goldstone bosons, of mass m_G, couple strongly with the neutrinos, affecting the acoustic oscillations during the eV era of the early universe that generate the peaks in the CMB radiation. Characteristic signals result over a very wide range of (f, m_G) because of a change in the total relativistic energy density and because the neutrinos scatter rather than free-stream. Thermodynamics allows a precise calculation of the signal, so that observations would not only confirm the late-time neutrino mass mechanism, but could also determine whether the neutrino spectrum is degenerate, inverted or hierarchical and whether the neutrinos are Dirac or Majorana.

The flavor symmetries could also give light sterile states. If the masses of the sterile neutrinos turn on after the MeV era, the LSND oscillations can be explained without upsetting big bang nucleosynthesis, and, since the sterile states decay to lighter neutrinos and pseudo-Goldstones, without giving too much hot dark matter.

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1 Introduction

With the confirmation of atmospheric neutrino oscillations in 1998, and, more recently, of large angle solar oscillations, the burning question of neutrino physics has become "Why are the lepton mixing angles so large?" The more fundamental question, of why the neutrinos have non-zero masses so much smaller than the charged leptons and quarks, is never heard — apparently the answer is already known. Treating the standard model without right-handed neutrinos as an effective theory below scale M, there is a single interaction appearing at dimension 5: $\ell\ell hh/M$, where $\ell = (\nu_L, e)$ represents the three lepton doublets. When the Higgs doublet h acquires a vacuum expectation value v, the neutrinos acquire masses

$$m_\nu \approx \frac{v^2}{M} \qquad \text{from} \qquad \frac{1}{M}\ell\ell hh. \tag{1}$$

The gauge symmetries act on the known particles to guarantee that the neutrinos will have very small, but non-zero, masses. However, perhaps the most exciting implication of the atmospheric neutrino data is that, if M is taken to be the Planck mass, this contribution to the neutrino mass is too small to account for the observed oscillation length. Neutrino masses are not relics from the gravitational scale, rather they must be understood by a non-gravitational field theory below the Planck scale.

Without doubt, the leading candidate for this new physics is the see-saw mechanism [1]. Introducing right-handed neutrinos ν_R with Majorana masses M_R and Yukawa couplings $\lambda\ \ell\nu_R h$, the effective theory below M_R contains neutrino masses

$$m_\nu \approx \frac{\lambda^2 v^2}{M_R} \qquad \text{from} \qquad \lambda\ell\nu_R h + M_R\nu_R\nu_R. \tag{2}$$

The see-saw mechanism is so plausible that we sometimes forget that we do not know if it is correct. The problem with the see-saw mechanism is that it is too simple: it does not predict any particles or interactions at energies below M_R, so that it cannot be directly tested. It is remarkable that the heavy Majorana right-handed neutrino, with the interaction $\ell\nu_R h$ at high energies, does lead to two indirect tests of the see-saw. The cosmological baryon asymmetry may be generated by leptogenesis [2], and, with the addition of supersymmetry, lepton flavor violation is generated in the slepton interactions [3]. However, even if reactions such as $\mu \to e\gamma$ are observed, these connections alone, while suggestive, will not convince me that the see-saw is correct. To be convinced one needs a theory that gives precise numerical predictions for observables.

It appears to be highly significant that the atmospheric data is explained if the scale M_R of lepton number breaking is within an order of magnitude or so of the scale for gauge coupling unification. This connection with grand unification is very exciting — within the context of

$SO(10)$ theories, one can aim for very predictive theories of flavor [4]. Precise numerical predictions follow if there are fewer parameters than observables. The best hope for the see-saw mechanism appears to be a highly predictive theory for quark and lepton masses, mixings and CP violation, including leptogenesis and lepton flavor violation. Several talks at this meeting suggest that $SO(10)$ is currently the most promising direction [5, 6, 7], but so far I am not convinced by any particular theory.

With the theoretical simplicity of the see-saw mechanism so obvious, it is with some trepidation that I devote the rest of this talk to an opposite viewpoint. Perhaps neutrinos are light not because they are inversely proportional to a large scale of lepton flavor symmetry breaking, $m_\nu \propto 1/M_R$, but because they are proportional to a low scale of lepton flavor symmetry breaking $m_\nu \propto f$ [8]. Apparently we discount this possibility because we think that unknown physics lies at high energies rather than at low energies. However, neutrino physics is full of surprises and we should explore all avenues. Indeed, dark energy suggests that we may have missed other fundamental physics at low energies.

2 Late-Time Neutrino Masses

In the standard model, masses for charged leptons and quarks, ψ, arise from Yukawa interactions $\lambda\bar{\psi}_L\psi_R h$. To understand the wide range of Yukawa couplings one frequently constructs theories of flavor at some flavor mass scale, M_{F_c}, based on flavor symmetries that involve a set of scalar fields, ϕ_c, that are charged under the flavor symmetry. The subscript c refers to the electrically charged fermion sector. In the effective theory at energy scales below M_{F_c}, the interactions that generate charged fermion masses have the form $(\phi_c/M_{F_c})^{n_c}\ \bar{\psi}_L\psi_R h$. If the fields ϕ_c acquire a hierarchy of vevs, f_c, the resulting charged fermion masses are given by

$$m_c = \left(\frac{f_c}{M_{F_c}}\right)^{n_c} v \qquad\qquad \text{from} \qquad\qquad \left(\frac{\phi_c}{M_{F_c}}\right)^{n_c}\ \bar{\psi}_L\psi_R h. \tag{3}$$

The charged lepton and quark mass hierarchies follow from both the hierarchies in f_c and from a variety of positive integers n_c, determined by the group theory. This global flavor symmetry breaking leads to a set of Goldstone bosons, G_c — familons. The experimental limits from such flavor-changing processes as $\mu \to eG_c$ and $K \to \pi G_c$ are very strong, and, since the interactions of G_c are proportional to $1/f_c$, the scale f_c is forced to be larger than about 10^{11} GeV. In these theories, the physics of flavor of the charged fermions must occur at very high energies.

It is possible to develop a very similar picture to explain the small neutrino masses [8]. For the neutrinos to be naturally much lighter than the charged fermions, it must be that the above flavor symmetry breaking leaves the neutrinos massless. The neutrino masses must be protected by some further approximate flavor symmetry. When this symmetry is broken by a set of flavor symmetry breaking vevs, f, of fields ϕ, the neutrinos finally pick up masses

$$m_{\nu_D} = \left(\frac{f}{M_F}\right)^n v \qquad \text{from} \qquad \left(\frac{\phi}{M_F}\right)^n \ell \nu_R h \tag{4}$$

for Dirac neutrinos, or

$$m_{\nu_M} = \left(\frac{f}{M_F}\right)^{2n} \frac{v^2}{M_R} \qquad \text{from} \qquad \left(\frac{\phi}{M_F}\right)^n \ell \nu_R h + M_R \nu_R \nu_R \tag{5}$$

for Majorana neutrinos. The breaking of the neutrino flavor symmetry leads to a set of Goldstone bosons, G. Actually these bosons are not exactly massless because the neutrino flavor symmetry is only approximate, so that G acquire very small masses, m_G, and become pseudo-Goldstone bosons (PGBs).

A crucial question is how large the symmetry breaking vevs f are — there must be some new physics at f. Since the G interactions are proportional to $1/f$, a low scale for f will mean that G have large interactions. However, since the symmetry breaking induced by f leads to mass for only the neutrinos, not the charged leptons or quarks, G couple only to neutrinos, and the experimental limits on them are extremely weak. The strongest limits on f come from cosmology and astrophysics rather than from the laboratory. The requirement that G not be in thermal equilibrium during big bang nucleosynthesis gives a limit on f of approximately

$$f \geq 10 \text{ keV}, \tag{6}$$

and a similar limit results from requiring that G emission did not cool supernova 1987A too rapidly. These are much stronger than any lab limit on $\nu_a \to \nu_b G$. Thus, in contrast to the case of quarks and charged leptons, the physics of neutrino mass generation need not occur at energies much higher than the weak scale — rather the relevant flavor symmetry breaking scale could be much lower than the weak scale: GeV, MeV or even in the multi-keV domain.

In the hot big bang the neutrinos are massless until the phase transition at which ϕ acquire their vevs f; hence we call our scheme "late-time neutrino masses." In this scheme the neutrinos are light because the symmetry breaking scale f is much less than the fundamental mass scale M_F of the physics of neutrino masses. There is clearly a very wide range of possibilities for these mass scales. One simple possibility is for Dirac neutrinos with $M_F \approx v$ and $n = 2$, giving $m_\nu \approx f^2/v$, so that $f \approx 100$ keV. In the Majorana case, small neutrino masses may be partly due to a small f/M_F and partly due to the usual see-saw mechanism. However, there is no need for any see-saw — the right-handed neutrinos could be at the weak scale. Unlike the see-saw mechanism, late-time neutrino masses work equally well for both Dirac and Majorana cases.

The spontaneous breaking of lepton symmetries is hardly new. However, the triplet Majoron model [9], which was originally seen as a way of protecting neutrino masses with a spontaneously broken lepton number symmetry, has long been excluded. On the other hand, the singlet Majoron model [10] is viewed as a possible origin for the heavy right-handed neutrino masses, M_R. It is non-trivial that $f \ll v$ is allowed by data, and this option for explaining why the neutrinos are so light has been sorely neglected.

A possible objection to late-time neutrino masses is that introducing a new scale f below the weak scale leads to a new hierarchy problem. However, it is simple to construct theories where f is generated and stabilized by a low scale of supersymmetry breaking in the singlet sector [8, 11], or by having composite right-handed neutrinos [12].

3 CMB Signals

In contrast to the see-saw mechanism, late time neutrino masses introduce new physics at low energy. In particular, there are very light PGBs with dimensionless couplings to neutrinos of order m_ν/f. In the early universe, successful big bang nucleosynthesis requires that G not be in thermal equilibrium during the MeV era, giving the constraint $f \geq 10$ keV. One might expect that G would therefore be irrelevant to cosmology. However, decays and inverse decays, $G \leftrightarrow \nu\nu$ or $\nu_3 \leftrightarrow \nu_{1,2} G$, depending on m_G, and the scattering process $\nu\nu \to GG$ have reaction rates with a recoupling form: as the universe cools, these reaction rates increase relative to the expansion rate, so that G can enter the thermal bath after nucleosynthesis. Indeed, any G will become thermalized for a very wide range of (f, m_G): for f as large as the weak scale and m_G as large as an MeV, as shown by the size of the signal region in Figure 1.

Any PGB brought into equilibrium by the eV era will leave a signal in the cosmic microwave background radiation (CMB). Furthermore, the size of the signal sheds light on the symmetry structure of neutrino mass generation, as well as the spectrum of neutrinos and whether they are Dirac or Majorana. The recoupling process itself does not alter the total relativistic energy density (usually parameterized by the effective number of neutrino species N_ν) — it just shares this energy density between the neutrinos and the PGBs. It is the processes happening after recoupling that give the crucial signal, and for a particular PGB the signal depends on whether its mass m_G is larger or small than the eV scale. PGBs with $m_G >$ eV decay back to neutrinos before the eV era. This process occurs at fixed entropy, meaning that the total relativistic energy density is increased. The angular peaks of the CMB radiation allow a measurement of the total radiation energy density during the eV era: $N_{\nu_{CMB}}$. Our prediction, shown in Table 1, depends on the number of such PGBs and whether the neutrinos are Dirac or Majorana. This signal is computed with very simple analytic formulas, similar to the case in the standard cosmology

n_G	Dirac	Majorana
1	3.09	3.18
2	3.18	3.34
8	3.62	4.08
16	4.08	-

Table 1: The effective number of neutrino species, $N_{\nu_{CMB}}$, during the eV era for 3 Dirac or 3 Majorana neutrinos recoupled to n_G PGBs heavier than 1 eV.

n_R	1	2	3
$N_{\nu_{CMB}}$	3.77	3.98	4.08

Table 2: The dependence of the total relativistic energy density during the eV era, $N_{\nu_{CMB}}$, on the number of neutrino species, n_R, to which the PGBs recouple. The case shown is for 8 PGBs and Majorana neutrinos.

of e^+e^- annihilation heating the photons relative to the neutrinos. The numbers given assume that all n_G PGBs recouple to all three neutrinos before the heaviest start to decay, and the well-known QED correction of +0.05 is not included.

The number of PGBs, n_G, reflects the original neutrino flavor symmetry. For 3 Dirac neutrinos, the maximal flavor symmetry is $SU(3)_L \times SU(3)_R$ leading to 16 PGBs, while for 3 Majorana neutrinos the maximal possibility is $SU(3)$, leading to 8 PGBs. The first year WMAP data limited $N_{\nu_{CMB}}$ to the range of about 1 to 6 [13], and hence was not sufficiently powerful to see these effects. The sensitivity expectations on $N_{\nu_{CMB}}$ from future experiments are about ± 0.20 for Planck and ± 0.05 for CMBPOL.

The signal in Table 1 assumes that each PGB recouples to all three species of neutrinos. However, a PGB coupling is proportional to m_ν/f, where here m_ν means some entry in the neutrino mass matrix. For a degenerate spectrum of neutrinos, if a PGB recouples to one neutrino species it will recouple to all three, since the coupling to each neutrino is comparable. On the other hand, depending on parameters, for a hierarchical spectrum the number of neutrinos the PGB recouples to, n_R, could be 1,2 or 3; and for the inverted spectrum $n_R = 2$ or 3, but not 1. The dependence of the $N_{\nu_{CMB}}$ signal on n_R is illustrated in Table 2.

A PGB with $m_G <$ eV remains in the bath during the acoustic oscillations that generate the peaks in the CMB, so there is no signal in $N_{\nu_{CMB}}$. However, the presence of the PGB in the bath causes an important change in the physics that generates the peaks, and hence leads to a new characteristic signal. The standard calculation of the CMB peaks assumes that the neutrinos do not scatter during the eV era, rather they free-stream from high temperature to low

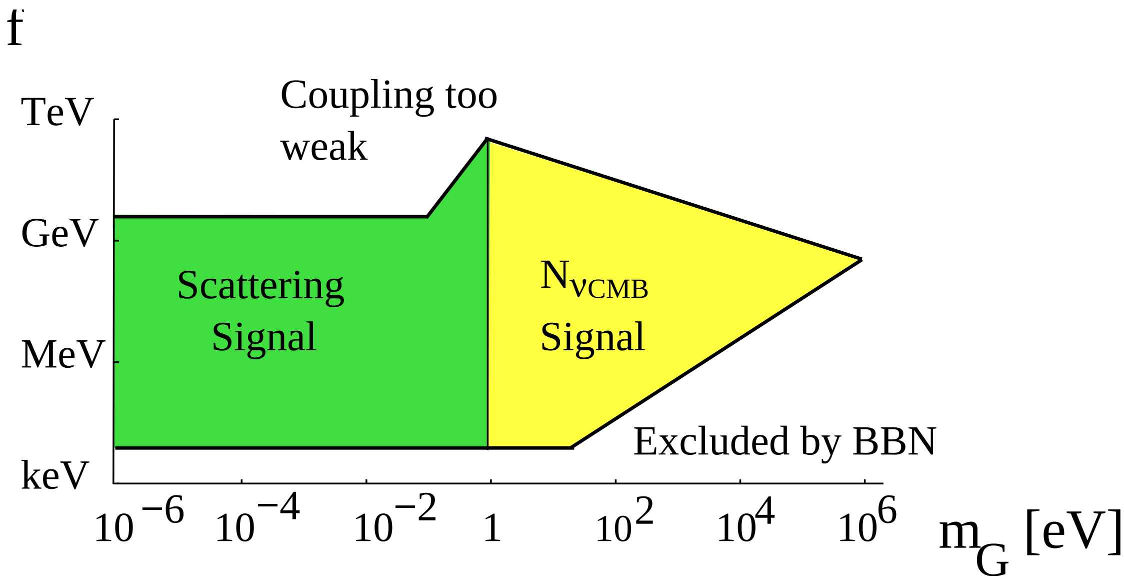

Figure 1: Signal regions and cosmological bounds for a single Majorana neutrino. CMB signals occur throughout the two shaded regions. We have assumed $m_\nu = 0.05$ eV.

temperature regions. This causes a well-known change in the appearance of the CMB peaks, and can be understood analytically as a being due to a change in the phase of the acoustic oscillations [14]. However, interactions with the background PGB, whether by $\nu_3 \leftrightarrow \nu_{1,2}G$ or by $\nu G \leftrightarrow \nu G$, prevent this free-streaming, and hence remove this phase that occurs in the standard picture. This gives a clear observational signature: a shift in the CMB peak for the nth multipole of

$$\Delta l_n = 7.8 n_{scatt}, \tag{7}$$

relative to the standard model calculations, where n_{scatt} is the number of neutrino species that are prevented from free-streaming by the interactions with G [8]. Other physical effects also shift the position of the peaks. But it should be straightforward to observe this large effect since it is a shift that is independent of the multipole n. Clearly one needs to obtain the position of as many peaks as possible.

From the Figure we see that the large signal region in (f, m_G) space is divided into two: an $N_{\nu_{CMB}}$ signal for $m_G >$ eV and a Δl_n signal for $m_G <$ eV. Since there may be many PGB, some heavier than others, both signals may be present. We have taken m_G as a free parameter, since the physical origin of the explicit flavor symmetry breaking that leads to m_G is very uncertain [8]. If explicit symmetry breaking arises from dimension 5 operators at the Planck scale, M_P, one expects $m_G^2 \approx f^3/M_P$, so that signals are expected for f in the range of 10 keV to 1 GeV.

4 Lepton Flavor Violation

In supersymmetric theories, a superpotential interaction of the form $\lambda \ell \nu_R h$ will lead to 1-loop radiative corrections in the slepton mass matrix at order λ^2, offering the prospect of probing the standard see-saw mechanism by a variety of lepton flavor violating interactions [3]. However, there is a major limitation to this signal: the radiative correction occurs at very short distances, governed by the large right-handed neutrino mass, M_R, and is absent if supersymmetry breaking has not yet appeared as local interactions in the slepton mass matrix at this high scale. Thus the signal is only present if the "messenger" scale of supersymmetry breaking, M_{mess}, is large enough

$$M_{mess} \geq M_R \simeq v \left(\frac{v}{m_\nu} \right). \tag{8}$$

Since M_R is typically around 10^{15} GeV, this is a very severe limitation.

With late-time neutrino masses, the physics of neutrino mass generation occurs at a much lower scale, enlarging the range of supersymmetry breaking scenarios for which there will be a lepton flavor violating signal. At energies below M_F and M_R, the operators responsible for neutrino masses are non-renormalizable, as shown in (4) and (5). To obtain a sizable signal the radiative correction must involve a renormalizable interaction. Thus one must go to sufficiently short distances to probe the origin of these non-renormalizable operators. The radiative correction can be generated at the scale M_R or M_F — much below the scale of M_R in the see-saw mechanism. For example, in the case of Dirac late-time neutrinos the signal is expected if

$$M_{mess} \geq f \left(\frac{v}{m_\nu} \right)^{1/n}. \tag{9}$$

Comparing (8) with (9): since $f < v$, this opens up a much wider region to lepton flavor tests, especially for $n > 1$. For example, if $f \approx$ GeV and $n = 2$ the requirement is $M_{mess} \geq 10^7$ GeV. In the Majorana case, signals typically persist for even lower messenger scales.

5 LSND Neutrinos

The LSND collaboration reported evidence for the oscillation $\bar{\nu}_\mu \to \bar{\nu}_e$ with a probability of 3×10^{-3} at the 3.8σ level [15]. This result is particularly intriguing: taken with the atmospheric and solar oscillations, it cannot be explained with the three known neutrinos, implying the existence of light sterile neutrinos. Combined fits to neutrino data are poor with only one such sterile state, and strongly prefer 2 or more [16] with at least one having a mass above 3 eV. The theoretical challenge of accounting for the LSND data without upsetting lab and cosmological constraints is almost insurmountable:

- Why are there light sterile states? This violates the elegant basis for the see-saw mechanism, that fermions without any standard model gauge interactions do not have their masses protected and hence should be very heavy.
- Neutrino oscillations in the big bang will populate the sterile states before big bang nucleosynthesis, leading to $N_{\nu_{BBN}} \geq 5$.
- Large scale structure surveys and WMAP have put a limit on the amount of hot dark matter in the universe, which translates to the sum of the neutrino masses being less than 0.7 eV [17]. The heavy LSND neutrino violates this by at least a factor of 4.

A confirmation of the LSND data by MiniBooNE [18] would herald a revolution in neutrino physics more profound than the confirmation of atmospheric and solar neutrino oscillations.

Late time neutrino masses provide a perfect reconciliation of the above difficulties in incorporating LSND oscillations [11].

- Lepton flavor symmetries act on right-handed neutrinos as well as left, and hence can naturally keep both light.
- If the flavor symmetries are broken below the MeV scale, $f <$ MeV, then the neutrinos are exactly massless during the big bang nucleosynthesis era. Since only the left-handed neutrinos feel weak interactions, $N_{\nu_{BBN}} = 3$.
- As the temperature drops beneath the mass of each sterile state, these states are removed from the early universe by decays to the three light neutrinos $\nu_s \to \nu_{1,2,3} G$. The decay rate is guaranteed to be large enough because $f <$ MeV implies large couplings of G to neutrinos, and the observed LSND oscillations imply that ν_s are mixed with the active states. Hence, the limit on hot dark matter applies only to the sum of the three light neutrino masses and the PGB masses: $m_{\nu_1} + m_{\nu_2} + m_{\nu_3} + \Sigma\, m_G$.

The nucleosynthesis constraint implies that f is so low that the PGBs will necessarily be thermalized before the eV era: if LSND oscillations are described by late-time neutrino masses, both types of CMB signal will *necessarily* occur. The relativistic energy density signal is now generated by the decay of the sterile neutrinos $\nu_s \to \nu_{1,2,3} G$, which happens before the eV scale because the sterile states are heavier than 1 eV. The prediction for $N_{\nu,\text{CMB}}$ is shown in Table 3, and depends on the number of PGB, n_G, and the number of sterile neutrinos.

Since the PGBs must be lighter than a few eV in order that the sterile states can decay, at least some of the light neutrinos scatter from G exchange, leading to a change in the multipole of the nth CMB peak

$$\Delta l_n = 23.3 - 13.1 \left(\frac{g_\nu (3 - n_{scatt})}{(3 g_\nu + n_G)(1/N_{\nu,\text{CMB}} + .23)} \right). \tag{10}$$

n_G	Dirac n_s			Majorana n_s		
	1	2	3	1	2	3
2	3.59	3.78	3.95	3.78	3.92	4.06
3	3.70	3.86	4.01	3.91	4.03	4.14
8	4.00	4.11	4.21	4.22	4.29	4.35

Table 3: Effective number of neutrino species during the recombination era, $N_{\nu,\mathrm{CMB}}$, in theories with LSND neutrino oscillations. The signal is produced by n_s sterile states decaying to n_G species of PGB and one of the three light neutrinos.

The large neutrino mixing angles suggest that all three neutrinos will scatter, $n_{scatt} = 3$, although $n_{scatt} = 2$ is also possible. The spin degeneracy is $g_\nu = 7/4, 7/2$ for Majorana, Dirac neutrinos. In all cases the signal is large.

6 Conclusions

While the see-saw explanation of small neutrino masses $m_\nu \propto 1/M_R$ is elegant and plausible, it does not generate any interactions at low energies that allow it to be directly tested. Even for the indirect tests, the predictions are only qualitative. We have proposed an alternative explanation: the neutrino masses are protected by a small lepton flavor symmetry breaking scale $m_\nu \propto f$ [8]. This symmetry breaking leads to a set of very light pseudo-Goldstone bosons, of mass m_G, with large interactions with the neutrinos. These interactions change the cosmological behaviour of the three known neutrinos before and during the eV era in a way which leaves a precise and characteristic signal on the CMB radiation. Within a given model for neutrino mass generation, the consequences for the total relativistic energy density and the scattering of the neutrinos are determined precisely by thermodynamics, and do not depend on unknown parameters. Hence, observations of these effects would tell us a great deal about the underlying theory: the symmetry breaking pattern, the neutrino spectrum and whether the neutrinos are Majorana or Dirac. Although other physics could lead to a deviation in $N_{\nu,\mathrm{CMB}}$ from 3, in a given theory we are able to make a precise numerical prediction. Furthermore, a shift in the multipole of the CMB peaks will tell us that the known neutrinos have a new interaction at low energy. A combination of both CMB signals, which results if some PGB are heavier than the eV scale and some lighter, would be convincing evidence for late-time neutrino masses.

With late time neutrino masses the right-handed neutrinos are much lighter than in the see-saw case. Hence, in supersymmetric theories the lepton flavor violating signals are expected for a much wider range of messenger scales for supersymmetry breaking, enlarging the interest in this indirect signal. However, it is the precise numerical predictions, for example of Tables 1,2 and 3 and equations (7) and (10), that we wish to stress.

The anti-neutrino oscillations observed by the LSND collaboration can be naturally described by late time neutrino masses; remarkably they imply signals in both $N_{\nu,\mathrm{CMB}}$ and the position of the CMB peaks [11].

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